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Final Technical Report

Imaging faults in induced earthquake zones using earthquake and controlled source data - North Texas and Northern Oklahoma

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Abstract

The 2016 USGS One-Year Seismic Hazard Forecast for the Central and Eastern US showed significantly increased hazard for North Texas, including the Dallas-Fort Worth Metroplex, and for northern Oklahoma. Over 2016, SMU operated a 30+ station seismic network in the North Texas to monitor and conduct research related to ongoing seismic sequences in Irving-Dallas and northeast Johnson County (Venus,TX) and pursue access to active source data for direct imaging of seismogenic faults in north Texas. Under G16AC00247 we expanded our focus beyond North Texas and used passive and active source seismic methods to image faults associated with induced earthquakes in both Texas and Oklahoma, outlined into four primary tasks. We successfully merged SMU local earthquake catalogs from 2008-present and expanded the catalogs for northeast Johnson County and the original 2008 DFW International airport sequence using template matching techniques. In both cases, low magnitude seismicity continues over a nearly 10-year period. In the DFW airport case, injection ceased soon after initial earthquakes in 2008-2009 but seismicity continues to spread north along the fault. In northeast Johnson County, high volume injection continues, and earthquake magnitudes have increased with time, the most recent event being the M_W 4.0 Venus earthquake in May 2015. Focal mechanisms data for over 200 earthquakes were used to invert for stress orientations within the basement rocks and build Mohr circle diagrams for the Azle, Venus and Irving/Dallas sequences. In all cases, earthquakes occur on faults critically oriented for failure in the modern stress field, supporting that hypothesis that small stress changes associated with fluid pressure increases due to wastewater injection are sufficient to reactivate pre-existing favorably oriented (i.e., NE-SW striking) normal faults in the basin. Efforts to directly image velocity heterogeneity using local earthquake tomography methods was unsuccessful, however. Continued work on active source data in the basin revealed the long-term history of deformation, or more explicitly, lack of recent deformation that would indicated continuous reactivation of basement faults over more recent times. In northern Oklahoma, efforts to bring a Vibroseis source into the IRIS Wavefield Experiment failed due to permitting issues. Instead, we added telemetry to the 18 broadband stations so that timely data on the M_W5.8 Pawnee, OK, earthquake could be made available to the community, including the Oklahoma Geological Survey and the US Geological Survey.

Introduction

Since 2008 the USGS ANSS catalog has reported over 200 earthquakes in North Texas, spatially associated with the Barnett Paleozoic total petroleum system in the Fort Worth Basin (FWB) (Figure 1). Of these, there have been five well-studied earthquake sequences in North Texas that were recorded using local seismic stations operated by SMU: 2008-2009 DFW Airport (Frohlich et al. 2010; 2011; Janska and Eisner, 2012), 2009 Cleburne (Justinic et al., 2013), 2013-2015 Azle-Reno (Hornbach et al., 2015; Phillips et al., 2014), 2014-2016 Irving-Dallas (DeShon et al., 2015a,b; Quinones et al., 2015), and 2015 Venus

(Scales et al., 2015; Lee et al., 2015; Scales et al., 2017) sequences. The SMU hypocenter catalog derived using data collected between 2013 – present now contains over 1500 hypocenters (Figure 2) obtained using 1D velocity models developed for each sequence, combined with standard detection, association, and locations methods provided in the Antelope software package (BRTT), as described in Hornbach et al. (2015). Higher-resolution earthquake locations are calculated using waveform cross-correlation and double-difference (DD) techniques. We calculate focal mechanisms for all events using P-wave first motions and S/P amplitude ratios, and, in some cases, use composite focal mechanisms to take advantage of the high degree of waveform similarity we see in North Texas. Integrated data of location information, fault plane solutions, information on subsurface geology, fault structure, well data, and 3D pore pressure modeling provide further insight into the relationship between fluid migration at depth and modern seismicity in North Texas.

In North Texas, earthquakes sequences can be characterized as swarms in that the first event is not the largest, and many of the sequences contain multiple, similar sized earthquakes (DeShon et al., 2015b). Causative faults strike NNE-SSW to NE-SW and are associated with normal faulting (Figure 3). Earthquake depths range from 2.0-8.0 km and are consistent with reactivation of ancient faults located in the Precambrian granites and overlying sedimentary units. Controlled-source imaging indicates that faults do not extend past the Early Pennsylvanian Marble Falls group (Magnani et al., 2015; 2017). The seismically active faults in the basement granites range from 2-6 km in length, dip 40-60^o to the SE or NW, extend from ~4-8 km depth below sea level, and are associated with fault areas of 10-15 km^2. Microseismic swarm activity, during which 100s of small earthquakes occur over hours to days during the Azle sequence, appear limited to failure within the Ordovician Ellenburger group, which serves as a wastewater injection unit in the basin and overlies the Precambrian granites. Hornbach et al. (2016) compile ~10 years of wastewater injection monthly volume and rate data for the FWB and show that earthquakes are spatially associated where cumulative injection volumes, and hence estimated pressure increases, are highest. The Azle sequence has been more directly linked to wastewater injectors located just west and north of the seismic sequence using pressure diffusion modeling (Hornbach et al., 2015). The Venus earthquakes are surrounded by large volume injectors located in Johnson County, and we suggest that the Venus sequence is also directly linked to wastewater injection (Scales et al., 2017). The fault dimensions illuminated by earthquakes and imaged by active source data are consistent with an intraplate fault system capable of generating high magnitude 4 or low magnitude 5 earthquakes, assuming standard earthquake scaling relations (e.g., Wells and Coppersmith, 1994).

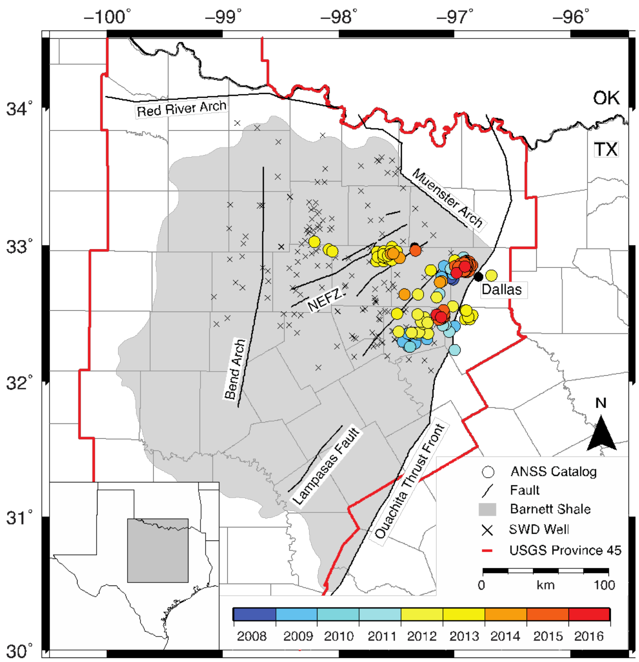

Figure 1. Map of the Bend Arch-Fort Worth Basin, Texas (USGS Province 45) showing regional faults [after Ewing, 1990] and major structural features. Over 200 earthquakes have been reported in the USGS ANSS catalog since 2008 (circles). Flowback fluids and brines produced as a byproduct of the hydrofracture stimulation process in the Barnett Shale play (gray) are disposed via reinjection into deep SWD wells (crosses) in Ordovician limestones, in stratigraphic contact with the Precambrian crystalline basement. NEFZ: Newark East Fault Zone. From Scales et al. (2017).

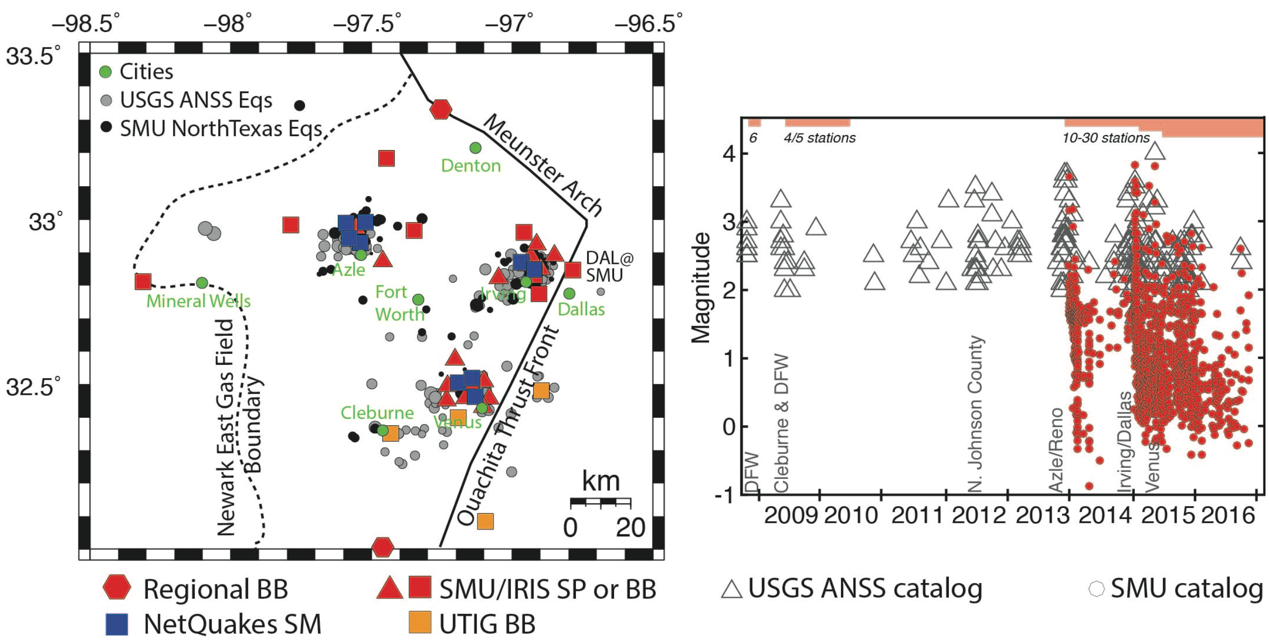

Figure 2. (left) Seismic stations in the FWB shown with both the USGS ANSS catalog (gray) and the SMU catalog (black) through December 2016. In addition to regional broadband stations (red hexagons), over the reported period SMU operated ~30 stations in collaboration with the TexNet and the Univ. of Texas Institute for Geophysics (UTIG, J. Walter) with instrumentation provided by the USGS and IRIS. The stations are a mix of short-period (triangles), intermediate & broadband (orange and red squares), and NetQuakes accelerometers (blue squares). (right) Magnitude versus time. The USGS ANSS catalog and SMU catalog 2013-present are shown. The SMU catalog local magnitudes have been calibrated to the USGS Lg body wave magnitude. Named earthquake sequences and deployment of local stations is marked.

Summary of Results from G16AC00247

SMU network operations, supported by the new Texas Seismic Network (TexNet) program, allowed us to continue to build a local earthquake catalog for the FWB. Over the reporting period, we implemented a new local magnitude calculator to bring the SMU local magnitude calculated within Antelope into better alignment with the USGS Lg body wave magnitude commonly reported for small events in the FWB (Figure 2). We also implemented revisions to focal mechanism calculations so that individual mechanisms are constrained by both P-wave first motion and S/P amplitude ratios (DeShon et al., 2016). Mechanisms are calculated using the HASH software (Hardebeck and Shearer, 2002, 2003). The SMU catalog contains 240 focal mechanisms (Figure 3), with highest quality mechanisms associated with the Venus and Irving/Dallas earthquake sequences. Station geometry changes in Azle over the course of the most active part of the seismic sequence limited our ability to obtain high quality mechanisms. Most mechanisms indicate normal faulting with B-axes parallel to strike of the associated fault (Figure 3). The data were inverted for stress orientation, which would reflect stress within the basement rock, and we find our results are similar to stress orientations reported for the overlying units in the FWB based on borehole breakout data (Snee and Zoback, 2016). Note that this work represents an expansion of Task 3 outlined in the original Cooperative Agreement.

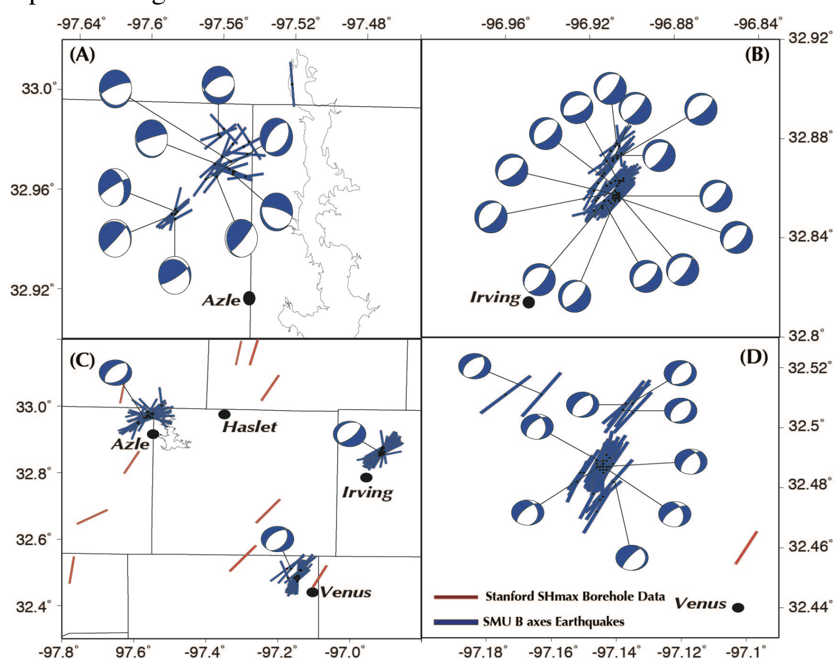

Figure 3: Map views of the three sequences in the FWB showing the B-axis orientations from earthquakes in basement rock, examples of generated focal mechanisms, and borehole break-out based stress orientations [Snee and Zoback, 2016]. Maps (A), (B), and (D) show the B-axis orientations of the Azle, Irving/Dallas, and Venus sequences along with a sample of the generated focal mechanisms for each sequence. Map (C) shows a zoomed out view of the Fort Worth Basin. The Snee and Zoback (2016) average SH_{max} value for the FWB was ~20ºNE, with some rotation noted from SE to NW.

Template matching work allowed us to extend the time history of events in both northeast Johnson County and under the Dallas Fort Worth International airport, and results indicate that once reactivated, faults can remain active over nearly decadal time scales (Scales et al., 2017; Ogwari et al., 2016; in preparation). A matched filtering approach was used to analyze regional recordings of earthquakes occurring in northeast Johnson County (Lee et al., 2015). Earthquakes recorded during the passage of the EarthScope TA (Frohlich, 2012) and associated with the M_W 4.0 2015 Venus earthquake sequence were used as templates. Earthquakes in this region appear to start within months of a second large injection well going online, and magnitude has increased over time (Figure 4) (Scales et al., in preparation). In the DFW airport area, template matching and relative relocation procedures indicate that the original 2008-2009 DFW sequence, which began within months of the start of nearby injection, has continued expanding to the northeast, albeit with highly variable rates, through 2015 (Ogwari et al., 2016; in preparation). The SMU 2013-present earthquake catalog contains two well-recorded events along the causative fault of the DFW sequence. These results stand in contrast to the 2013-2014 Azle sequence, which appears to rather abruptly begin in November 2013 based on regional waveform correlation studies (B. Keller, personal communication; M. Brudzinski, personal communication), although peak cumulative injection from two nearby wells occurred in 2011 (Hornbach et al., 2015). Note that this work represents an expansion of Task 2 outlined in the original Cooperative Agreement.

Using North Texas data, we attempted to image active faults using local earthquakes recorded by the SMU seismic network by applying double-difference (DD) tomography methods. The goal was to resolve potential Vp/Vs ratio changes associated with pore fluid pressure changes hypothesized to be a driving mechanism in inducing earthquakes. Due to uneven raypath coverage biased heavily by upgoing raypaths, we were unsuccessful in resolving significant velocity heterogeneity along the fault (Sufri et al., 2016). Essentially, solutions with geologically unreasonable slow shallow velocities and fast near-source velocities yield the same travel time residual reduction as solutions with fast shallow velocities and slow near-source velocities. We have found no 3D solution that fits the available travel time data better than the 1D models designed for each of the FWB seismic sequences. Task 1 as described in the CA was unsuccessful, and we think efforts to directly image velocity on faults using local earthquake tomography techniques are best left for the Oklahoma datasets where earthquakes are larger and hence recorded on stations at a variety of distances. We continue our efforts to constrain the 3D velocity heterogeneity of the FWB using other approaches and the inclusion of TexNet and other data sets.

During the duration of the CA, efforts continued to refine the tectonic and structural context of the area of the Venus sequence, to identify and to constrain the geometry (e.g. length, dip, strike) and history of deformation of the fault(s) that host the seismicity in the Johnson County area. A total of 32 km of 2D seismic reflection data, obtained as part of the 2015 SMU-USGS CA, were analyzed, stratigraphic and structural interpretation finalized and the data integrated with the seismic passive source data and wastewater injection data. All seismic reflection data were available as post-stack upon purchase, so that analysis in the pre-stack domain could not be performed. Two of three purchased lines were available in time migration domain, and, to compare earthquake hypocenter locations and imaged features, we worked with T.Pratt (USGS-Reston) to bring all profiles to time migration and then depth conversion. The 1D velocity function used for time to depth conversion was derived from the gradient function used for seismicity relocation, calibrated on the depths of the regional stratigraphic boundaries in the area, as constrained by nearby well logs. The tops of the main stratigraphic units were identified on well logs using gamma ray and resistivity information, when available. The tops were then projected onto the nearest seismic profile, correlated with reflectors and the interpretation propagated to the nearby seismic profiles at crossing points, resulting in an internally consistent interpretation (Scales et al., in preparation).

The interpretation of active source data in the Venus area also contributed to an additional collaboration with M. Blanpied (USGS-Reston) on a comparison between seismic reflection data acquired across active and quiescent faults in the Central U.S. intraplate region in areas where deformation is unequivocally caused by tectonic processes (e.g., the New Madrid seismic zone in the northern Mississippi embayment and surrounding region) and in areas where causes are still debated (i.e., Fort Worth basin, North Texas). Careful analysis of the available data in both basins shows different long-term behavior of faults, revealing that while in regions where tectonic processes are at work faults display a long-lived activity, in regions of intense wastewater injection where seismicity appears to be a novel phenomenon, faults offsets are not resolved beyond Lower Pennsylvanian sequences, indicating that the faults have been dormant for the past 300 Myrs until the recent surge of seismicity in 2008 (Magnani et al., 2017). Note that this work represents an expansion of Task 3 outlined in the original Cooperative Agreement.

In Oklahoma, efforts centered on successful collection of, and facilitating real-time access to, the IRIS Wavefield Initiative community experiment (ie., Anderson et al., 2016; Sweet et al., 2016). The IRIS experiment deployed 363 modern 3-component 4.5Hz seismic nodes, 18 broadband stations and 9 infrasound instruments centered on a small, active fault in Grant County, OK. The goal of the program was to capture the full wavefield of local and regional earthquakes and explore innovative instrumentation and array designs. Originally, G16AC00247 was to provide funds to pay for a Vibroseis source to contribute valuable P and S-wave data for direct imaging of the targeted fault; however, this could not take place as planned because the local authorities declined to issue a field permit for the active seismic source survey effort. In light of the M_W 5.8 Pawnee earthquake September 3, 2016, we received permission to reallocate funds to pay for real-time community access the Wavefield Experiment broadband seismic data. Wavefield data was successfully telemetered between late September and mid-November, 2016 and directly archived with the IRIS Data Management Center. The Oklahoma Geological Survey incorporated the data into their standard processing (J. Chang, personal communication), and we presume the USGS National Earthquake Information Center did as well.

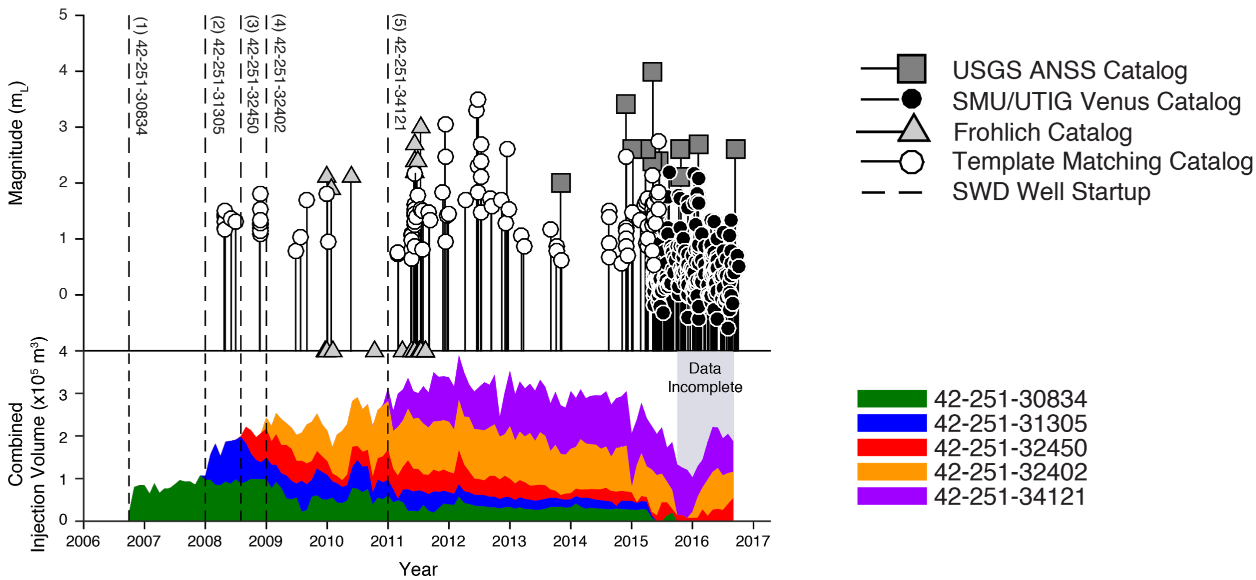

Figure 4: *Top:* Earthquake activity in the Venus region from 2008 through the end of 2016. The matched-filter detections (white circles), Frohlich 2012 catalog (gray triangles), ANSS catalog (gray squares), and local SMU/UTIG catalog (black circles), show increasing magnitude with time. Note that some Frohlich 2012 catalog earthquakes do not have reported magnitudes [Frohlich, 2012]. ANSS catalog earthquakes are within 5 km of local catalog centroid. The 5 nearest SWD wells (shown in Figure 2) begin operations starting in late 2006 (dotted lines) and are labeled numerically and by API number. *Bottom:* Injection volumes of the 5 nearest SWD wells (onset of injection activity represented by continuation of dotted lines) over time. Colors show proportion of individual injection well volumes to total volume. From Scales et al. (2017).

Completion of Tasks under G16AC00247

Task 1: Fault Imaging using earthquakes and local earthquake tomography. DD tomography imaging of the three ongoing North Texas sequences was technically completed but failed to yield new information regarding 3D velocity heterogeneity near reactivated basement faults in the FWB. The local earthquake datasets contain primarily upgoing raypaths and hence controlling velocity tradeoffs in depth will require additional information. In Azle, we have a chance to constrain near surface S-wave velocity using ambient noise recorded on a dense 110 station 1C 10HZ nodal deployment, and we continue to work on ways to constrain inversions for velocity within the basin. Both positive and null results were presented at the 2016 AGU meeting (Sufri et al., 2016).

Efforts to constrain the geometry of active faults in the basin using waveform correlation and DD locations techniques continue to be successful in the FWB and were outlined in the previous section.

Task 2: Template matching, regional location accuracy and identification of the initial hypocenters associated with induced earthquake swarms. Template matching, matched filter and related correlation methods continue to be a powerful technique to explore induced earthquake sequences. Results for North Texas were discussed in the previous section. The DFW work by P. Ogwari technically was not funded under this CA but we felt the results directly spoke to the goals outlined under the CA. Additionally, it is important to recognize that in North Texas, local networks have generally been deployed after a significant swarm of felt earthquakes has begun and then, usually due to funding, these networks are removed before the smallest earthquakes have ended. Template matching can help fill in this before and after piece and provide number of earthquakes, relative size and relative epicenter; constraining depth using regional recordings remains an issue.

We continue to be interested in a collaboration with the USGS Induced Earthquake group on a publication assessing the temporal patterns of induced earthquakes recorded to date across the CEUS. Over this 6-month period, H. DeShon stayed in contact with J. Rubinstein (USGS) regarding work on swarm vs mainshock/aftershock characterization of areas of induced seismicity. However, no direct collaboration via publication developed in the time frame of the CA, which notably included the M_W 5.8 Pawnee earthquake.

Task 3: The North Texas high resolution earthquake catalog, focal mechanisms, and timely access to industry seismic data. Results for this task were outlined above and we deem this task complete and successful. Under this task, joint reanalysis of industry controlled source data by M.B. Magnani (SMU) and T. Pratt (USGS-Reston) in northeast Johnson County was completed and results are included in Scales et al., (in preparation). Additionally, analysis and comparison of seismic reflection data in the Fort Worth basin and the Mississippi embayment in the Central US performed in collaboration by M.B. Magnani and M.Blanpied (described above) is completed and the results are included in Magnani et al., 2017.

Task 4: Bringing controlled seismic sources to the IRIS Wavefield Experiment. A summary of the history of this task was included in the previous section. While it is unfortunate that Grant County did not allow the Vibroseis portion of the experiment to take place, we believe that timely access to the broadband recordings of the Pawnee aftershock sequence was helpful to the community, including USGS scientists.

Additional Cooperation: Throughout the life of the 2016 CA, SMU continued to work with USGS on hazard-related issues, including collaboration through the Dallas County Earthquake Working group. Efforts were presented by M. Blanpied at the 2016 Fall AGU meeting (Blanpied et al., 2016).

Data Management

All continuous seismic data is archived with the IRIS DMC under FDSN network code 4F (Venus 2015-2016, doi:10.7914/SN/4F_2015) and FDSN network code ZW (Azle & Irving/Dallas 2013-2016, doi:10.7914/SN/ZW_2013). The IRIS Wavefield Experiment is archived under FDSN network code YW. The SMU hypocenter catalog is available upon request until publication in the peer-reviewed literature.

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